First Measurement of the Interference Fragmentation Function and Outlook on the Measurement of local P-odd Effects in Fragmentation at Belle

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Abstract. Using unpolarized electron-positron annihilation at center of mass energies near 10.58 GeV, light quark fragmentation functions can be measured with the Belle detector [1] located at the KEKB collider at KEK, Japan. Using azimuthal correlations of unpolarized hadron yields in separate hemispheres in two-jet events, transverse spin dependent fragmentation functions are measured. These functions can be used as quark polarimeters sensitive to the transverse polarization of partons in the proton in semi-deep inclusive scattering off the proton or proton-proton scattering. This so-called transversity distribution is poorly known compared to other leading-twist, collinear parton distribution functions mainly due to its chiral-odd nature, which makes inclusive measurements of this function infeasible [2]. So far it could only be accessed using transverse spin dependent fragmentation functions measured at Belle. Namely the Collins Fragmentation Function which leads to the Collins effect in SIDIS and p-p and the Interference Fragmentation Function leading to di-hadron correlations which is discussed here. If one allows not only chiral-odd but also parity odd fragmentation functions, the parity odd fragmentation function $\tilde{H}_1^{\perp}$ can lead to azimuthal asymmetries in the produced pion yields. Even though global parity violation is experimentally constrained to be very small, local parity violating effects mediated by coupling to instantons and sphalerons can lead to sizeable effects in e+ e- annihilation. This article will give an overview over recent results for di-hadron correlations from which the Interference Fragmentation Function can be extracted and plans to measure local p-odd effects.

Keywords: Interference Fragmentation Function, transversity, local strong parity violation
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THE BELLE EXPERIMENT

The Belle experiment at KEK is described in detail here [1]. It was located at the KEKB collider detecting particles produced in the collision of electrons with an energy of about 8 GeV and positrons with an energy of about 3.5 GeV. The Belle experiment has good particle ID using time of flight, dE/dx measurements in the central drift chamber (CDC) aerogel cherenkov counters, electromagnetic calorimetry and RPCs outside the superconducting solenoid. Tracking capabilities are provided by a silicon vertex detector and the CDC in a 1.5 T magnetic field. The detector has full azimuthal coverage and a smooth acceptance, which is important for the detection of azimuthal correlations since the unpolarized beams do not allow the construction of asymmetries in which acceptance effects cancel. Belle profited from world record instantaneous luminosity provided by KEKB, which reached more than $2.11 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{1}$ and allowed the collection of more than 1 ab^{-1} integrated luminosity.

INTERFERENCE FRAGMENTATION FUNCTION MEASUREMENTS

The transverse spin dependent fragmentation of light quarks into unpolarized hadron pairs can be described by the Interference Fragmentation Function (IFF) $H_1^{\triangleleft}(z, m_{\mathrm{Inv}})$, where z is the fraction of the quark momentum the two hadrons are carrying and m_{Inv} is their invariant mass [5]. With this function the normalized yield $\mathcal{N}$ of di-hadron pairs can be described as

$$\mathcal{N}(z_1, z_2, m_1, m_2, \theta) \propto \cos(\Phi_1 + \Phi_2) B(\theta) \frac{\sum_q e_q^2 H_1^{\triangleleft}(z_1, m_1) \bar{H}_1^{\triangleleft}(z_2, m_2)}{\sum_q e_q^2 D_1(z_1, m_1) \bar{D}_1(z_2, m_2)}, \tag{1}$$

with the kinematic factor $B(\theta) = \frac{\sin^2\theta}{1+\cos^2\theta}$ giving the transverse polarization of the quark-antiquark with respect to its momentum. The angle θ is measured between thrust axis and beam axis in the CMS. Therefore the effect is largest in the acceptance region of the Belle barrel to which we restrict our analysis. The angles $\Phi_{1,2}$ are the azimuthal angles between the event plane and the difference vector between the two hadron momenta in each hemisphere. After being proposed by Collins, Ladinsky and Heppelman [5] the cosine modulation outlined in eq. 1 was measured by us for the first time for charged pion pairs as outlined in [6]. Figure 1 show the results for the amplitude $a_{1,2}(\theta, z_1, z_2, m_1, m_2) \cos(\Phi_1, \Phi_2) \propto \mathcal{N}$ differential in z_1, m_1 and integrated over z_2,m_2. The dependence on z is almost linear which is expected since at high z more of the spin information of the initial quark is passed on to the final state hadron. Only at low invariant masses the z dependence is flat. The dependence on the invariant mass of the hadron pair exhibits a richer structure. Around the mass of the ρ meson the amplitude peaks in line with model calculations in which an enhancement of the IFF comes from the interference of the p-wave amplitude in which a pion pair is produced from a ρ resonance and the s-wave amplitude of non-resonant pion production. Compared with the Collins Fragmentation Function which also has been measured at Belle [4], the IFF allows a complementary access to transversity that is free from some of the experimental and theoretical difficulties since the $H_1^{\triangleleft}$ dependent term in the cross-section does not vanish upon integration over intrinsic transverse momenta. Therefore collinear factorization can be used in the extraction of transversity and in experiments the initial quark momentum does not have to be known, making jet reconstruction in p-p unnecessary. In fact, the measurement of the IFF presented here together with measurements of di-hadron correlations by the HERMES collaboration have led to the first extraction of transversity in the collinear framework from di-hadron correlations [7].

PLANS TO MEASURE PARITY VIOLATING FRAGMENTATION FUNCTIONS

Recently charge dependent azimuthal correlations in heavy ion collisions indicative of local strong parity violation have been measured [8]. These effects are thought to be caused by non-perturbative gluon configurations, instantons and sphalerons, transitioning between QCD vacuum ground states. On a microscopic scale, quarks coupling to

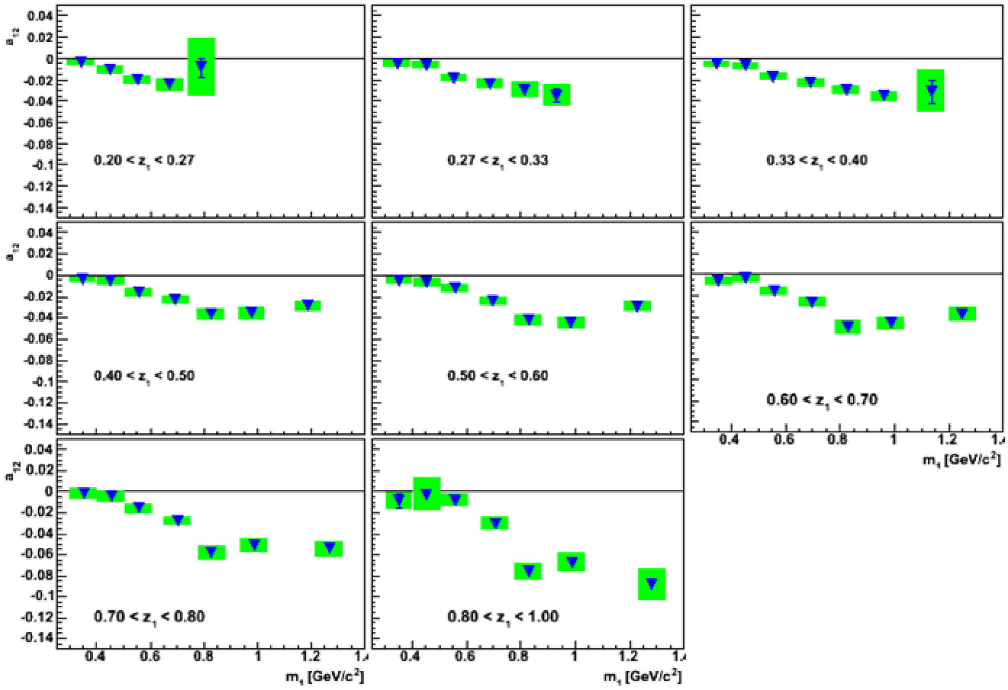

FIGURE 1. Results for di-hadron pair correlations in $e^+ - e^-$ annihilation at Belle

these configurations can lead to parity violating spin momentum correlations, which, in the presence of strong magnetic fields, lead to charge separation. In heavy ion collisions these magnetic fields are caused by off-center collisions, providing some of the strongest magnetic fields on earth [9]. However, heavy ion collisions are an extremely challenging environment to understand and there are competing explanations for the observed correlations. Compared to HI collisions, $e^+ - e^-$ is a very clean environment and as proposed by Kang and Kharzeev [3] quarks fragmenting in the above described parity violating "‘bubbles"’ can lead to measurable effects there as well. If parity odd terms are allowed in the expansion of the fragmentation matrix, the cross-section of the process $e^+ + e^- \to (q \to h_1 + X) + (\bar{q} \to h_2 + X)$ will contain a term $\sin(\Phi_1 + \Phi_2)$ where the azimuthal angles $\Phi_{1,2}$ are the azimuthal angles defined between the momenta of hadrons $h_{1,2}$ and the event plane much like in the measurement of the IFF and the Collins function. In fact, the sine modulation originates from one quark fragmenting via the Collins FF $H_1^\perp$ and the other quark by its parity violating pendant $\tilde{H}_1^\perp$. The cross-section also contains a $\cos(\Phi_1 + \Phi_2)$ term that contains contributions from $H_1^\perp * \bar{H}_1^\perp$ and $\bar{H}_1^\perp * \bar{\tilde{H}}_1^\perp$ which is parity-even. One way to look at this effect is, that one (anti-) quark fragments in the parity violating bubble with spin and momentum aligned. The spin direction is then given by the polarization analyzing properties of the Collins FF. Since it is experimentally impossible to determine if the quark or antiquark is fragmenting via $\tilde{H}_1^\perp$ the sign of the modulation varies event by event. Therefore the parity-odd effect averages out, making the cross-section parity even consistent with measurements of global parity violation. These event-by-event fluctuations also makes the effect extremely hard to measure, since it has to be measured event-by-event as well.

Measurement Technique

Due to the low particle multiplicities it is not possible to do a significant measurement event-by-event. Instead we extract sine-moments over all events. Due to the unknown sign the mean of the extracted moments will be zero. However, the distribution of the extracted asymmetry will be wider, ideally double peaked. The reference distribution will come from Monte-Carlo techniques, using Pythia and a GEANT simulation of the Belle detector already used to do systematics studies for the IFF and Collins FF extractions. Since a simple disagreement between simulated and real data obviously does not have to have its origin in physics, there needs to be a check if a difference is an indication of a physics effect or just of a poor simulation. Fortunately the dependence on the kinematic factor $B(\theta)$ provides just such a check. Any effect linear in $B(\theta)$ is transverse spin dependent and thus physical. Further systematic checks that we do are comparisons to mixed events and measuring the ratio of the effects for like and unlike sign pion pairs, which probe different combinations of favored and unfavored fragmentation functions.

OUTLOOK

The knowledge of fragmentation functions is crucial for the extraction of the transverse spin structure from semi-inclusive measurements. In addition to providing a tool to study the spin structure of the nucleon, we can also study the structure of the QCD vacuum in $e^+ - e^-$ annihilation. Presented here are new results for the transverse spin dependent Interference Fragmentation Function into charged pion pairs and our plans to extract local parity violating effects. In the future we plan to measure the IFF and the Collins Fragmentation Function for other particle and charge combination. Of special interest are IFF measurements with neutral pions in the final state, because these channels are expected to have larger effects in p-p collisions due to the charge independent coupling. Also, large Collins asymmetries for kaons in SIDIS experiments motivate the measurement of the corresponding kaon fragmentation function. Another missing piece in the analysis of di-hadron correlations is the measurement of unpolarized di-hadron fragmentation functions.

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